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Retrieving CCN column density from single-channel measurements of reflected sunlight over the ocean: A sensitivity study

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Abstract. The Twomey effect is an increase of the cloud albedo with increasing concentration of tropospheric aerosols serving as cloud condensation nuclei (CCN). Confirmation and quantification of this effect on a global basis requires accurate satellite retrievals of CCN concentrations. We present a theoretical study of the ability of passive satellite remote sensing techniques to provide reliable estimates of tropospheric aerosol column densities over the ocean. We show that a retrieval algorithm based on single-channel single-viewing-angle radiance measurements is incapable of accurately determining CCN column densities and that an algorithm based on multiangle radiance measurements provides much better retrievals. However, even for the latter algorithm the errors in the retrieved CCN column densities can exceed a factor of 5. The poor performance of single-channel radiance-only algorithms is explained by the strong dependence of the extinction cross section and weak dependence of the phase function on aerosol effective radius. In contrast, high-precision multiangle polarization measurements, which are much more sensitive to aerosol microphysics, are capable of constraining CCN column densities to within a few tens of percent.

1. Introduction

The indirect effect of tropospheric aerosols on climate could be the main missing climate forcing substantially offsetting greenhouse warming (e.g. *Hansen et al.* [1997] and references therein). Accurate quantification of this effect requires the determination of radiation flux changes to a high decadal precision and global measurements of changes in aerosol and cloud properties and is only achievable through use of instruments onboard Earth-orbiting satellites.

One possible manifestation of the indirect aerosol effect, usually referred to as the Twomey effect [*Twomey*, 1974], assumes that the cloud droplet number density increases with an increase in the number concentration of aerosol particles serving as cloud condensation nuclei (CCN). If the cloud liquid water content remains constant, the decrease of the extinction cross section per cloud particle due to the decrease in the particle radius is more than offset by the increase in the cloud droplet number density. As a result, the cloud optical thickness and thus the cloud albedo increase.

Confirmation and quantification of the Twomey effect on a global basis require accurate satellite measurements of CCN column densities. An obvious way of retrieving the number N of tropospheric aerosols in the vertical column of unit horizontal cross section is to divide the satellite-retrieved aerosol optical thickness τ by the average extinction cross section per particle C_{ext}. Since C_{ext} depends on the aerosol size distribution and refractive index, the determination of N requires a model of aerosol. The model can be either assumed a priori, as done in the advanced very high resolution radiometer (AVHRR) algorithm [*Rao et al.*, 1989], or retrieved simultaneously with τ, as planned in more advanced algorithms [*Diner et al.*, 1996; *Kaufman and Tanré*, 1996; *Mishchenko and Travis*, 1997a; *Herman et al.*, 1997]. In both cases errors in the retrieved optical thickness and in the assumed/retrieved aerosol model cause errors in the derived aerosol column density. *Mishchenko and Travis* [1997a,b] (hereinafter papers 1 and 2, respectively) have compared the ability of different satellite remote sensing techniques to retrieve the aerosol properties important in calculating the direct radiative forcing. However, the sensitivity of these techniques to aerosol concentration has not been examined so far. Therefore, we analyze the ability of passive satellite measurements to provide an accurate retrieval of CCN column densities. For simplicity, we consider only retrievals over ocean since the ocean reflectance is low and can be rather accurately characterized. We perform a sensitivity analysis using numerically accurate calculations of (polarized) radiative transfer in a realistic atmosphere-ocean model and theoretically simulate several types of aerosol retrievals utilizing single-channel radiance and/or polarization measurements of reflected sunlight.

2. Computer Simulations

We follow the approach developed in paper 1 and use precomputed radiance, I, and normalized second and third Stokes parameters, q and u, for a large set of "candidate" aerosol models with effective radii r_{eff} varying from 0.005 to 0.8 μm in 0.005 μm increments, refractive indices m varying from 1.35 to 1.65 [*d'Almeida et al.*, 1991] in steps of 0.005, and optical thicknesses τ ranging from 0 to 0.4 in steps of 0.005. The aerosol is assumed to be nonabsorbing, single-component, and monomodal with radii obeying a gamma size distribution [*Hansen and Travis*, 1974] with a fixed effective variance of $v_{eff} = 0.2$. We restrict the analysis to a single near-infrared wavelength of $\lambda = 0.865$ μm and assume ocean surface roughness corresponding to the global average of the long-term annual mean wind speed (7 m/s). A detailed description of the model and numerical techniques used can be found in paper 1.

We consider two strategies of single-channel satellite measurements, namely, what we call the AVHRR strategy (reflectance and/or polarization measurements of a scene are acquired at only one viewing angle) and the multiangle imaging spectroradiometer (MISR) strategy (employing multiple-viewing-angle radiance and/or polarization measurements of a scene). The illumination and viewing directions are specified by the cosine of the solar zenith angle μ_0 (fixed at 0.8), cosine of the satellite zenith angle μ, and relative satellite-sun azimuth angle φ. For the MISR type of measurements μ varies from 0.2 to 1 in steps of 0.2 in the satellite orbit plane specified by $\varphi = 60°$ and $-120°$ thus yielding nine viewing directions covering the range of

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scattering angles from 82° to 148°. For the AVHRR type of measurements the viewing direction is given by $\mu = 0.6$ and $\varphi = -120°$, thus yielding a scattering angle of 103.9° in the same orbit plane.

Computer-simulated data includes the quantities I, q, and u for a "standard" aerosol model with $\tau_0 = 0.2$, $r_{\mathrm{eff},0} = 0.3$ μm, and $m_0 = 1.45$. These "standard" parameters are representative enough of the accumulation mode of sulfate aerosols in terms of the typical aerosol loading and average microphysical characteristics. We then assume that the aerosol model is unknown and attempt to reconstruct the "unknown" optical thickness, effective radius, and refractive index by comparing the reflectivity and/or polarization computed for the standard model with those for each of the candidate models from the large precomputed set. We use three acceptance criteria which are intended to model retrievals using radiance measurements only (criterion A), polarization measurements only (criterion B), and radiance and polarization measurements combined (criterion C). The first two criteria are given by

$$\frac{1}{N_\mathrm{v}} \sum_{j=1}^{N_\mathrm{v}} \frac{|I_c^j - I_s^j|}{I_s^j} \le \Delta_I, \tag{A}$$

$$\frac{1}{N_\mathrm{v}} \sum_{j=1}^{N_\mathrm{v}} \frac{1}{2}\left[\,|q_c^j - q_s^j| + |u_c^j - u_s^j|\,\right] \le \Delta_P, \tag{B}$$

where the superscript j numbers the viewing directions (N_v = 1 for the AVHRR type and 9 for the MISR type of measurements), the subscripts s and c label quantities pertaining to the standard and candidate models, respectively, and Δ_I and Δ_P are the photometric and polarization instrumental accuracies. The third criterion, (C), is fulfilled if and only if both (A) and (B) are fulfilled. The criteria select those candidate models for which the computed radiance and/or polarization do not deviate from those for the standard model by more than the assumed measurement errors. For the MISR type of measurements the candidate-standard model deviations are averaged over the nine viewing directions. All candidate models that pass the acceptance criteria are equally good solutions so that none can be preferred as the unique retrieval.

As shown in paper 2, the fact that the measurement errors Δ_I and Δ_P are never equal to zero results in multiple acceptable solutions. This is demonstrated in Figures 1a–1f computed for the AVHRR and MISR types of retrievals assuming the expected earth observing scanning polarimeter (EOSP) radiance and polarization accuracies $\Delta_I = 4\%$ and $\Delta_P = 0.2\%$ [*Travis*, 1992]. The intersection of the white dashed lines in Figures 1b and 1e indicates the standard model (correct solution). The green color shows all candidate (τ, r_eff, m)-combinations (for m = 1.35, 1.45, and 1.6) that passed the radiance-only acceptance criterion (A), the magenta color shows the result of applying the polarization-only criterion (B), and the intersections of the green and magenta areas show the result with criterion (C). The performance of the AVHRR type radiance-only algorithm is especially poor, so that errors in the retrieved aerosol parameters τ, r_eff, and m are unacceptably large. This is not an unexpected result since it is hard to anticipate that an algorithm based on a single measurement can retrieve three unknown parameters with a high accuracy [*Diner et al.*, 1996; paper 1]. That is why the actual AVHRR algorithm [*Rao et al.*, 1989] is based on assuming rather than retrieving the aerosol model and retrieves only τ. However, Figures 1a–1c clearly show that assuming wrong r_eff and m can result in very large errors in the retrieved optical thickness. Therefore it is not surprising that comparisons with direct measurements of τ show errors in the AVHRR optical thickness retrievals exceeding 100% [*Ignatov et al.*, 1997].

The use of nine measurements in the MISR type radiance-only algorithm (green areas in Figures 1d, 1e, and 1f) improves the retrieval significantly but still does not constrain all three aerosol parameters with the precision needed for an accurate evaluation of the direct aerosol radiative forcing [*Hansen et al.*, 1995]. The latter is fully achieved only with the multiangle polarization algorithm (magenta area in Figure 1e). The absence of magenta areas in Figures 1d and 1f demonstrates the sensitivity of the multiangle polarization algorithm to refractive index (paper 1). The combined use of multiangle radiance and polarization (intersection of green and magenta areas in Figure 1e) further improves the retrieval accuracy, but not much.

As mentioned, errors in the retrieved optical thickness and assumed/retrieved aerosol model inevitably lead to errors in the retrieved aerosol column density. The blue-and-red background in each panel of Figure 1 is a color contour plot of the ratio $\beta = [\tau\, C_\mathrm{ext}(r_{\mathrm{eff},0}, m_0)]/[\tau_0\, C_\mathrm{ext}(r_\mathrm{eff}, m)]$ and, in combination with the green and magenta areas, shows the possible range of the ratio of the retrieved to the actual aerosol column densities for the different types of aerosol retrievals. Note that the color bar is strongly nonlinear and that the white color marks the regions where the ratio N(retrieved)/N(actual) does not deviate from unity by more than ±10%. Because of the relatively weak dependence of the extinction cross section on refractive index (paper 1), the blue-and-red background does not change much as m increases from 1.35 to 1.6.

Figures 1a–1c show that the region of possible β values for the AVHRR type intensity-only algorithm spans many orders of magnitude, thus indicating that this type of retrieval is unsuitable for a reliable determination of CCN column densities. The MISR type intensity-only algorithm provides a much better retrieval. However, even with this type of measurements the errors in the retrieved column density are much larger than those in τ, r_eff, and m and can exceed a factor of 5. Errors of this magnitude are still too large for a reliable quantification of the Twomey effect [*Schwartz and Slingo*, 1996]. Only the multiangle polarization algorithm determines the aerosol model with such a precision that the retrieved aerosol column density is constrained to ±10% (Figure 1e).

3. Discussion and Conclusions

Our results show that the determination of the CCN column density with radiance-only measurements is a much more difficult problem than retrieving the aerosol optical thickness. The origin of this difficulty lies primarily in the strong dependence of the extinction cross section on the effective radius (Figure 2). In the absence of absorption C_ext increases as the sixth power of r_eff for $r_\mathrm{eff} \ll \lambda$, as the second power of r_eff for $r_\mathrm{eff} \gg \lambda$, and as an intermediate power for wavelength-sized particles [*Hansen and Travis*, 1974]. Therefore a factor of two error in the retrieved/assumed r_eff results in a factor of 4 error in the retrieved column density for very large particles and in much larger errors for wavelength-sized and sub-wavelength-sized particles (see the definition of the ratio β and Figure 1). As a result, a rather weak dependence of the aerosol phase function on r_eff makes the radiance-only algorithms poorly sensitive to the aerosol column density. Although we have shown simulations for only one standard aerosol model, similar calculations suggest that one may expect comparable or even larger errors for other standard models. On the other hand, polarization is strongly dependent on the aerosol model; it can change not only the magnitude but even sign with changing r_eff and/or m (Plate 3 of paper 1). Furthermore, polarization is a ratio of two intensity components and can be measured to a much higher precision than intensity [*Travis*, 1992]. These two factors make the multiangle polarization algorithm a much more accurate tool for determining aerosol column densities, as Figure 1 clearly demonstrates.

An important feature of our sensitivity study is that all aerosol parameters (τ, r_eff, and m) are assumed to be unknown,

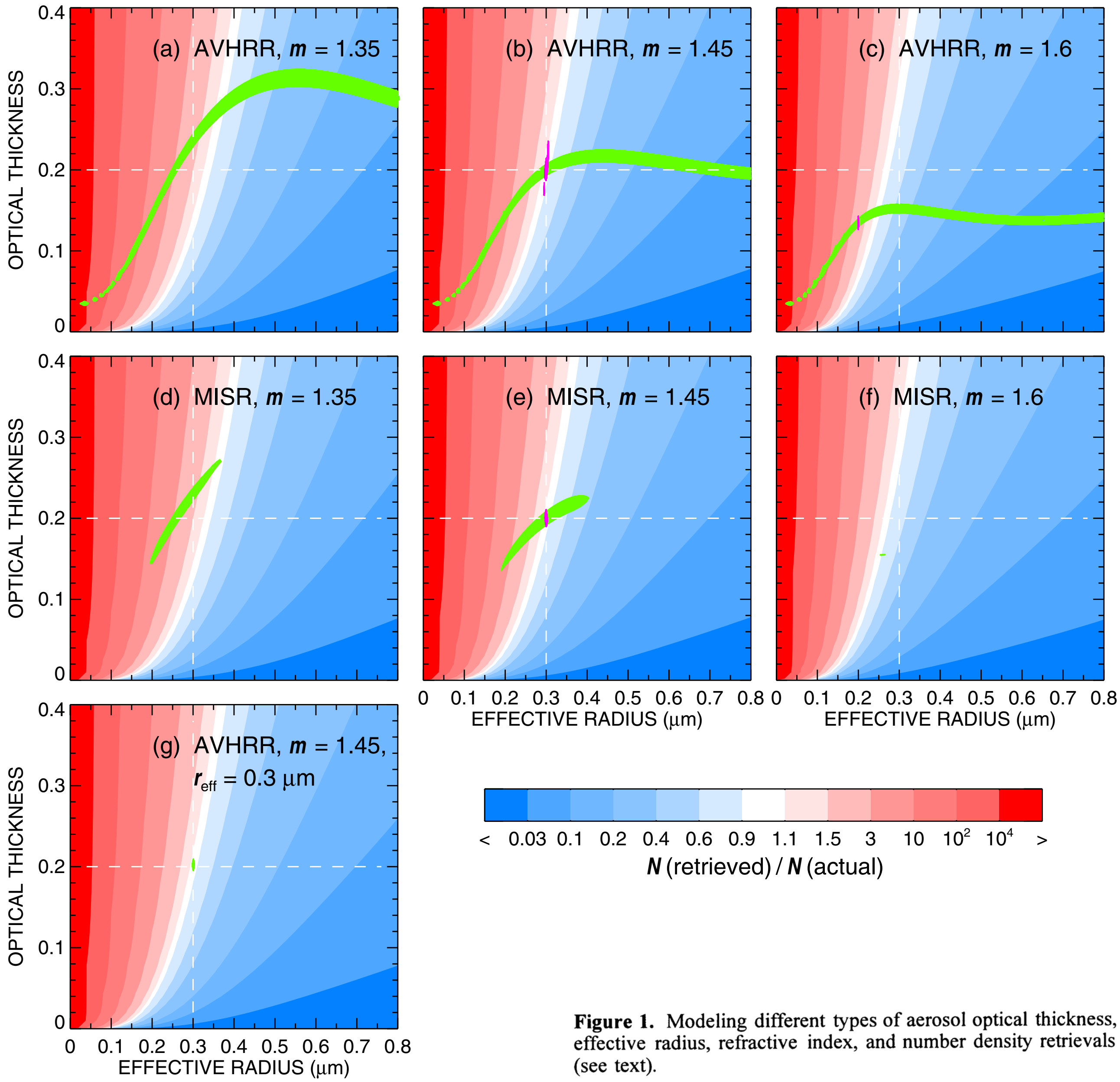

Figure 1. Modeling different types of aerosol optical thickness, effective radius, refractive index, and number density retrievals (see text).

which is the usual situation in practice. However, a common approach is to consider all model parameters but one to be known beforehand and to assume that retrieval errors in the single unknown parameter result solely from measurement errors. Figure 1 demonstrates that this approach can grossly overstate the retrieval accuracy. Indeed, if r_{eff} and m are known precisely and the radiance measurement accuracy is 4%, then the green area in Figure 1g shows that the accuracy of retrieving τ with the AVHRR intensity-only algorithm is better than ± 0.02. However, relaxing the constraints on r_{eff} and m dramatically expands the range of acceptable solutions (green areas in Figures 1a, 1b, and 1c) and drastically degrades the optical thickness retrieval accuracy. This is because nonzero measurement errors allow equally good fits to the measurements with model parameters far from the actual ones.

A factor which was neglected in this study is aerosol absorption. The analysis of paper 2 shows that neither radiance-only algorithms nor polarization-only algorithms nor their combination can be used to retrieve the aerosol single-scattering albedo w with sufficient accuracy. However, paper 2 demonstrates that accurate polarization retrievals of the aerosol optical thickness and aerosol model do not require a precise knowledge of w, whereas uncertainties in w can strongly degrade the accuracy of radiance-only retrievals. Therefore the potential abundance of absorbing aerosols in the troposphere [*Hobbs et al.*, 1997] can pose an additional problem for radiance-only retrievals of the aerosol column density, but not necessarily for polarization-based retrievals.

Another limitation of our analysis is that we considered algorithms based on single-channel measurements. Instruments such as the moderate resolution imaging spectrometer (MODIS) [*King et al.*, 1992] and MISR [*Diner et al.*, 1996] will measure radiances at several wavelengths, and the use of multispectral information may be expected to improve the sensitivity of

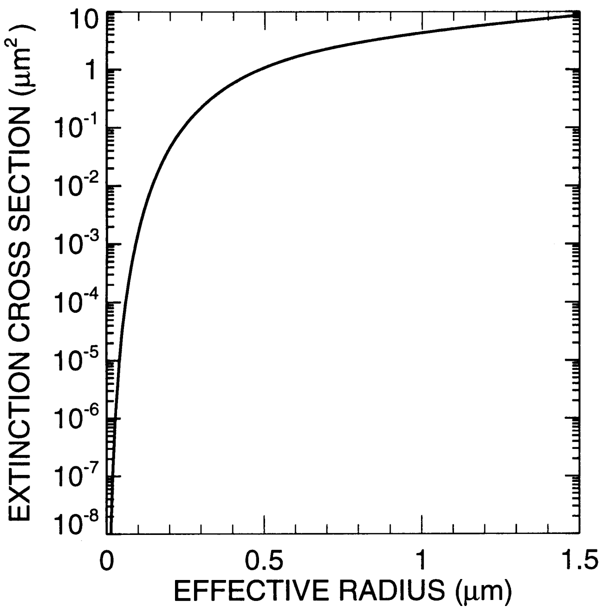

Figure 2. Extinction cross section versus effective radius for a gamma distribution of aerosols with $m = 1.45$ and $v_{\mathrm{eff}} = 0.2$.

radiance-only algorithms to aerosol model and, thus, aerosol column density. However, this still needs to be demonstrated since additional spectral radiances provide truly independent information only if aerosol refractive index and single-scattering albedo do not change with wavelength; otherwise addition of each new channel adds at least two new unknown quantities (channel-dependent real and imaginary parts of the refractive index) which must also be retrieved from the measurements. For example, the sensitivity study by *Jorge and Ogren* [1996] shows that inversions of direct spectral measurements of optical thickness can result in large errors in the retrieved size distribution and are strongly sensitive to the assumed wavelength dependence of the refractive index. The MODIS and MISR algorithms invert spectral radiance measurements rather than spectral optical thickness measurements, which inevitably makes them even less sensitive to aerosol model. Therefore, a sensitivity study similar to this one is necessary in order to show how accurate multispectral radiance-only retrievals of CCN column densities can be. In any case, our comparison of different remote sensing techniques under exactly the same conditions clearly suggests that retrievals based on high-precision, multiangle measurements of polarization as well as radiance at one or several wavelengths should always outperform similar algorithms employing radiance measurements alone. This superiority of polarization-based retrievals from an instrument such as EOSP, which will have the same spectral coverage as MODIS, should be especially important in more challenging situations than that analyzed here, e.g., when aerosol is multimodal or multicomponent, or when the natural variability of such quantities as the surface wind speed and water vapor concentration are taken into account.

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